The far-infrared absorption of a periodic 2DEG in the transition regime between weak and strong modulation

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We study the optical absorption of arrays of quantum dots and antidots in a perpendicular homogeneous magnetic field. The electronic system is described quantum mechanically using a Hartree approximation for the mutual Coulomb interaction of the electrons. The evolution of the absorption is traced from the homogeneous to the strongly modulated case identifying the ensuing collective modes, the magnetoplasmons, and their correlations with inherent length scales of the system.

Key words: Arrays, quantum dots, antidots, far-infrared absorption.

Technically it is possible to tune a gate-modulated lateral superlattice from the case of quantum dots to antidots. In a short period structure the consistent inclusion of the Coulomb interaction is essential in order to correctly model the ground state and the far-infrared (FIR) absorption of the two-dimensional electron gas (2DEG).

The square array of quantum dots or antidots is represented by the periodic potential

$$V_{\text{per}}(\mathbf{r}) = V \left\{ \sin\left(\frac{\pi x}{L}\right) \sin\left(\frac{\pi y}{L}\right) \right\}^2 \quad , \qquad (1)$$

where L is the periodic length of the array. The ground-state properties of the interacting 2DEG in a perpendicular homogeneous magnetic field and the

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periodic potential are calculated within the Hartree approximation for the Coulomb interacting electrons at a finite temperature [1]. The FIR absorption of the system is calculated within the time-dependent Hartree approximation perturbing the 2DEG with an incident electric field

$$\mathbf{E}_{\text{ext}}(\mathbf{r}, t) = -iE_0 \frac{\mathbf{k}}{|\mathbf{k}|} \exp\left\{i\mathbf{k} \cdot \mathbf{r} - i\omega t\right\} \tag{2}$$

with finite, but small wavevector $|(k_x L, 0)| = 0.2$. The power absorption is found as the Joule heating of the self-consistent time-dependent electric field composed of the external field and the induced field [2].

We use GaAs parameters, $m^* = 0.067m_0$, $\kappa = 12.4$, and assume $L = 100$ nm and $T = 1$ K. The absorption is calculated for the magnetic field $B = 1.24$ T, leading to the cyclotron energy $\hbar\omega_c = 2.14$ meV and the magnetic length $l = 23$ nm. In figure 1 the absorption is presented as a function of the external frequency ω for several values of the modulation V. The electron density is
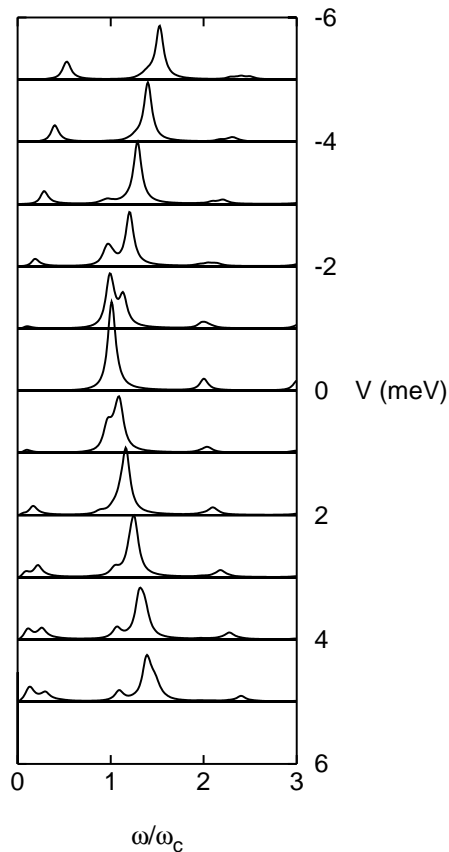

Fig. 1. The FIR absorption as a function of the scaled frequency ω/ω_c and the modulation V. $L = 100$ nm, $B = 1.24$ T, $N_s = 0.5$, $l = 23$ nm, and $T = 1$ K.

low, on the average one electron per two unit cells of the array, $N_s = 0.5$. This is possible since we are dealing with extended Bloch-like states. The model can thus not describe what happens in the tight-binding limit. In the unmodulated case, $V = 0$, three Bernstein peaks are visible [2–5], (The one with the highest frequency is located just at the right edge of the figure). The generalized Kohn theorem predicting one magnetoplasmon peak is broken by the small wavevector of the incident electric field. The general structure of the peaks is otherwise not modified by the small nonzero wavevector. Slight modulation, positive or negative, causes the main Bernstein peak to broaden giving it two maxima reflecting the van Hove singularities of the active band, (the band the elctrons are excited into). The main peak is blue-shifted with increasing modulation as the energy separation of the bands is determined by $(\hbar\omega_c)^2$ and V^2 for low electron density.

For the evolving dot array, $V < 0$, a simple two peak structure emerges as the electrons get increasingly localized in the dot minima. The 'confining' potential the electrons see approaches slowly the parabolic form necessary for the Kohn's center-of-mass modes as can by verified by the time-dependent induced density. If the magnetic field is lower than here, and l thus larger, the confinement will be poorer and more effects of the band structure due to the periodic array are visible. In other words, the coupling of individual dots is stronger. Figure 2 shows the electron density in the case of the lower magnetic field $B = 0.41$ T.
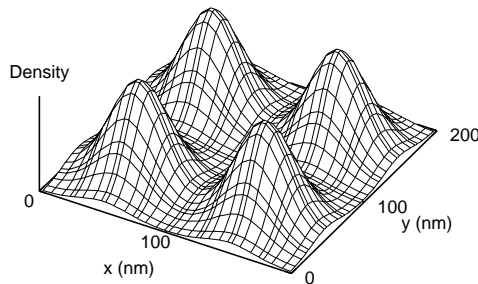

Fig. 2. The electron density of a quantum dot array in arbitrary units in four unit cells. Two electrons occupy the shown area, $N_s = 0.5$. $L = 100$ nm, $B = 0.41$ T, $l = 40$ nm, and $T = 1$ K.

In the limit of an antidot array, $V > 0$, we also obtain essentially the expected two peak structure. The antidot array supports a richer variety of collective modes that depend sensitively on the relation of l to L [6,7]. The induced density can be used to identify the lower peaks with skipping orbits around individual antidots, the upper peaks with oscillation of the density between four antidots. Still higher peaks are caused by perturbed linear waves travel-

ling along the array in the direction of the incident radiation but acquiring a wavelength L, rather than the one imposed on the system by the external electric field.

To which extent the single dots in an array are coupled can be fine tuned by the magnetic field B, the electron density N_s/L^2, and the modulation V assuming that L is constant. Even for the strongest modulation chosen here, $V = -5$ meV, band structure or coupling effects can be brought into play by reducing the magnetic field.

The evolution of the Berstein modes can here be traced from the unmodulated homogeneous 2DEG to the cases of arrays of dots or antidots. Their existence has also been verified experimentally in isolated wires and dots, and in self-consistent models of single dots and wires [4].

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